SHAFTS AND SURVEY ERRORS OF ANCIENT TUNNEL ENGINEERING IN JERUSALEM AND CAESAREA WATER SYSTEMS, ISRAEL

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Abstract
Ancient tunnels are some of the best sites to test ancient engineering techniques. Several late Hellenistic (?) - Roman period water tunnels in Israel are studied in order to identify surveying problems associated with two types of shafts, inferred by deviations in the meeting points of the digging teams. In general, vertical shafts are better than inclined shafts in terms of tunnel survey and construction. However, there must be a reason why inclined shafts were preferred (over vertical ones) in some occasions. A possible reason for this could be the need for people to descend down the shafts for regular maintenance of the tunnel where this was needed. Studied inclined shafts had steps which allowed easier access down the shafts into the tunnel. However, inclined shafts gave rise to surveying problems and associated deviations in the underlying tunnel. The meeting of the two digging teams could be assisted by acoustic communication, which was an ancient practice in Israel, utilized already in Iron Age (~700 BCE) tunneling.
Keywords: water tunnel, survey errors, shaft, Jerusalem low-level aqueduct, Caesarea water system.

Riassunto
Gli antichi tunnel sono fra i migliori siti per testare antiche tecniche di ingegneria. In Israele numerosi tunnel idraulici di età tardo ellenistica (?) - Romana sono stati studiati per individuare problemi associati a due tipi di pozzi, desunti dalle deviazioni nei punti di incontro delle squadre di scavo. In generale i pozzi verticali sono migliori di quelli inclinati ai fini della progettazione e della realizzazione. Tuttavia in alcune occasioni sono stati preferiti i pozzi inclinati rispetto ai pozzi verticali. Una possibile ragione potrebbe essere individuata nella necessità di raggiungere più facilmente il condotto sotterraneo per l'ordinaria manutenzione della struttura. I pozzi inclinati presi in esame presentavano gradini che permettevano un più facile accesso al tunnel ma potevano anche essere all'origine di problemi di rilievo e a relative deviazioni della galleria sottostante. L'incontro fra le due squadre di scavo potrebbe essere stato facilitato dal contatto acustico, che era un'antica pratica utilizzata in Israele per la realizzazione di gallerie già nell' età del ferro (~ 700 a.C.).
Parole chiave: *tunnel idraulici, errori di indagine, pozzo, acquedotto di Gerusalemme bassa, sistema idrico Cesarea.*

Introduction

Ancient development of surveying techniques allowed water systems to be concealed underground, often using long tunnels (Forbes, 1956). Bedrock tunnels connecting two points were often used as shortcuts across topographic barriers. Their construction involved relatively sophisticated surveying techniques, compared with subaerial aqueducts.

Tunneling commonly involves three surveying stages: (1) subaerial survey between the two tunnel ends and designing the tunnel route; (2) transferring the planned directions to the underground; this may be performed through the tunnel entrances by measuring horizontal line of sight, and through narrow intermediate shafts; (3) surveying along the newly excavated tunnel segments.

The surveying should be accurate enough to allow meeting of two excavating teams. Because of propagation of errors, which is inevitable in surveying, the two teams may miss the planned meeting point. Acoustic communication can be used to rectify this and finally meet the other team. The tunnels studied here were dug with the aid of intermediate shafts, each serving as a starting point for two excavation teams which met a team approaching from the opposite direction. The meeting point of the two teams and its close proximity provides us with an opportunity to directly measure the deviations associated with surveying errors. The horizontal deviations can be clearly deduced from modern maps of the ancient tunnels.

The development of surveying techniques in the Hellenistic-Roman period (e.g. Vitruvius, translated by Morgan, 1960) must have had an impact on tunnel surveying. Yet, actual usage of particular instruments is debatable, particularly in remote regions of the large empires. The observed deviations in tunnel construction may be used to determine the dispersal of new techniques. We study tunnels whose width is similar to that of humans, because wider tunnels may indicate later widening which can obliterate the signs of initial deviations.

Intermediate shafts are not a prerequisite for tunnel construction. Although using shafts in tunnel construction is an ancient technique, some tunnels without shafts predate the tunnels with shafts which are discussed below.

Some of the oldest water tunnels with intermediate shafts are known from the Assyrian empire (e.g. Oleson, 2008). Assurnasipal II (884-859 BCE) built a canal which passed through a rock ridge at Negoub via a tunnel seven km long, dug between pairs of vertical shafts. Assyrian tunnels were constructed

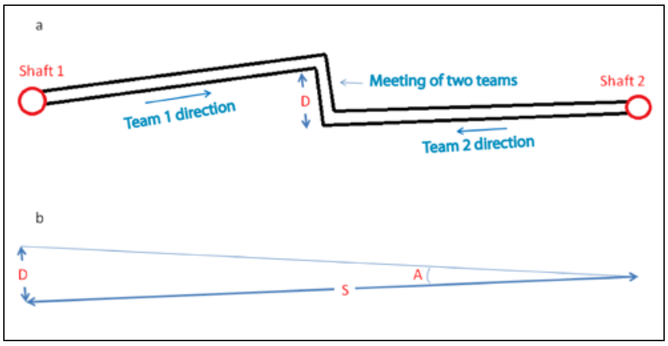

Fig. 1: (a) schematic plan of a theoretic tunnel segment between two shafts, S (m) apart. From the bottom of each shaft a team of excavators hewed the tunnel towards each other, with a final deviation of D (m) close to the meeting place, where acoustic communication was used to rectify the deviation. (b) Schematic representation of the angular deviation A: A= arctg D/S.

Fig. 1: (a) pianta schematica teorica di un segmento della galleria tra due pozzi, a distanza S (m). Dalla base di ciascun pozzo una squadra di scavatori procedeva nella galleria verso l'altra, con una deviazione finale D (m) presso il punto di incontro, dove la comunicazione acustica era utilizzata per rettificare l'errore. (b) Rappresentazione schematica della deviazione angolare A:A= arctg D/S.

in short segments between successive intermediate shafts, spaced a few tens of meters apart (Safar, 1947; Reade, 1978; Davey, 1985). Reducing long tunnels into short segments allowed the teams to find each other underground, thus avoiding the need for sophisticated tunneling and surveying techniques. The shafts also served other purposes during the initial digging and the use of the system. This technology spread later to the Greek and Etruscan worlds (Oleson, 2008). Ancient tunnel engineering is a major topic studied by Italian scholars (e.g. Parise, 2011; Parise et al., 2009,2013). Geological constraints involved in the realization of artificial caves were reviewed by Del Prete and Parise (2013).

The Siloam tunnel in Jerusalem was constructed ~700 BCE (Frumkin et al., 2003). This unique tunnel can serve as a baseline for long tunnels technology in the southern Levant. The tunnel is 533 m long, without intermediate shafts constructed to bring water from the Gihon Spring into the city. A combination of geological and archaeological evidence demonstrate that the circuitous route of Siloam tunnel and the final meeting of the two excavating teams are associated with continuous modifications of the plan to allow acoustic communication between diggers and surface teams (Frumkin et al., 2003).

A longer tunnel (1040 m) without intermediate shafts was constructed during the early 6th century BCE by Eupalinos on the island of Samos (e.g. Kienast, 1984; Oleson, 2008). The tunnel crossed a ridge taking as short a route as was feasible, with two teams working from both ends. Accurate surveying measurements were undoubtedly needed here.

Other Hellenistic tunnels from the 6th century BCE onwards maintained the Mesopotamian method, digging the tunnel outward from a series of intermediate shafts (Bromehead, 1942). Tunneling with intermediate shafts was commonly practiced by the Romans (Pliny, republished 1963; White, 1984). Vitruvius (1960) recommended an interval of 36 m between the shafts. The large number of these tunnels outside Israel is beyond the scope of this paper.

Here I discuss several late Hellenistic (?) - Roman period water tunnels in Israel to identify surveying problems associated with two types of shafts, inferred by deviations in the meeting points of the digging teams.

Methods

The ICRC performed a detailed survey of selected Roman period tunnels in Israel, using tape, compass, and inclinometer. This was done in tunnels which were incorporated in the water systems of two of the most important Roman period centers of the country: two tunnels of Jerusalem water system (Armon Hanatziv, and Dahr Baku), and two tunnels of Caesarea high-level aqueduct (En Ami and Dam shafts tunnels, both at Nahal Taninim). Data from the published survey of Jisr ez-Zarqa tunnel at Caesarea high-level aqueduct (Porath, 2002) were also incorporated in this study.

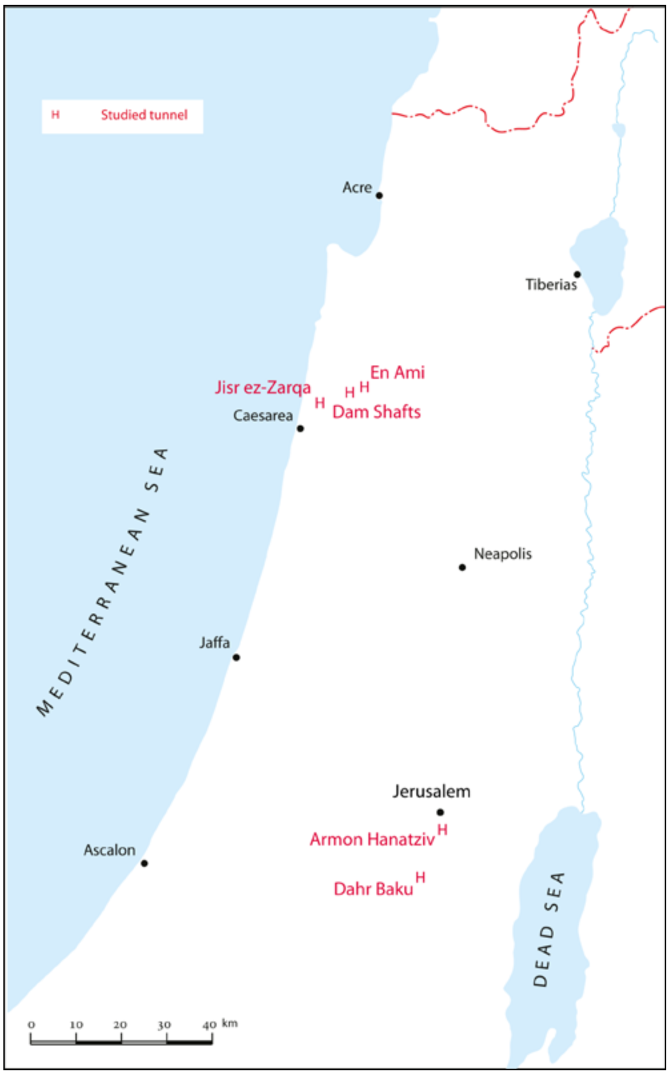

Fig. 2: location of studied tunnels, belonging to Jerusalem and Caesarea water systems.

Fig. 2: ubicazione delle gallerie studiate appartenenti ai sistemi idrici di Gerusalemme e Cesarea.

Tunnel name	probable age	shafts #	shaft distance m	deviation at meeting m	angle error	shaft type
Armon Hanatziv	1st century BCE	1*2	24.1	0	0	vertical
'		2*3	102.1	0	0	vertical
		3*4	135	0	0	vertical
		4*5	44.2	0	0	vertical
		5*6	41	0	0	vertical
Jisr ez-Zarqa	1st century	10*11	27.1	0	0	vertical
		11*12	37.6	0	0	vertical
		12*13	36.9	0	0	vertical
		13*14	33.8	0	0	vertical
		14*15	35	0	0	vertical
		15&16	31.8	0	0	vertical
		16C1	33.1	0	0	vertical
		17&18	40.1	0.6	0.9	vertical
		18&19	28	0	0	vertical
		19&20	25.5	0	0	vertical
		20&21	31.8	0	0	vertical
		21&22	34.4	0	0	vertical
		22&23	14	0	0	vertical
		23&24	11.5	0	0	vertical
		24&25	14.6	0	0	vertical
		25&26	22.3	0	0	vertical
MEAN ANGULAR DEVIATION BETWEEN VERTICAL SHAFTS (DEGREES)						**0.04+/-0.19, n=21**
Dahr Baku	1st century BCE	1&	29.8	0	0	inclined-vertical
		2&	55.2	7.4	7.6	inclined
		3&	35.6	5.9	9.5	inclined
		4&	48.1	3.7	4.4	inclined
		7&	48.9	8.9	10.3	inclined
		8&	53.3	10.4	1	inclined
		9&10	48.3	0	0	inclined
		10&11	55.6	0	0	inclined-vertical
Taninim En Ami	Roman period	1&	37.2	5.8	8.9	inclined
		2&	34.9	3.5	5.7	inclined
		3&	25.6	0	0	inclined
		4&	45.3	20.9	24.8	inclined
		5&	40.7	7	9.7	inclined
		6&	44.2	0	0	inclined
		7&	46.5	3.5	4.3	inclined
Dam Shafts	Roman period	1&2	48.2	8.2	9.7	inclined
		2&3	44.7	7.1	9	inclined
MEAN ANGULAR DEVIATION BETWEEN INCLINED SHAFTS (DEGREES)						**7.7+/-5.9, n=15**

Tab. 1: deviations at the junctions of the teams of the discussed tunnels.

Tab. 1: deviazioni in corrispondenza del punto di incontro delle squadre nei condotti in esame.

From these surveys, the following distances were extracted: (1) the distance between neighboring shafts; and (2) the horizontal deviation at the meeting of digging teams at each segment of the tunnel (Fig. 1).

The angular deviation A between adjacent shafts is defined as: A= arctg D/S where D is the deviation distance (in m) between the two teams at the proximity of the junction. S is the horizontal aerial distance (in m) between neighboring shafts.

The angular deviation is regarded as non-dimensional measure of the deviation, as it is normalized to the distance between the shafts. This measure of the deviation is independent of the initial plan of the tunnel route. The mean angular deviation was compared with other attributes of each tunnel, in order to explain the deviations in terms of Roman surveying and construction techniques.

Armon Hanatziv tunnel, Jerusalem low-level aqueduct

Jerusalem low-level aqueduct was the most important aqueduct leading to the city. It collected water from sources around Solomon's Pools, south of the city (Fig. 2). Built about the 1st century BCE (MAZAR, 2002; BILLIG, 2002), the aqueduct was used until the 20th century CE. Just south of Jerusalem, the aqueduct crosses a ridge via the 402 m long Armon Hanatziv tunnel, shortening the aqueduct route by 3.5 km. The tunnel had six vertical shafts, 24 to 135 m apart, and up to 40 m deep, associated with the variable depth from the ridge top (Fig. 3). Changes in tunnel direction at shafts 3 and 5 indicate that the original excavation was conducted from the bottom of each shaft to both directions. Original toolmarks are not well preserved due to the friable bedrock (Senonian chalk) and later modifications of the tunnel.

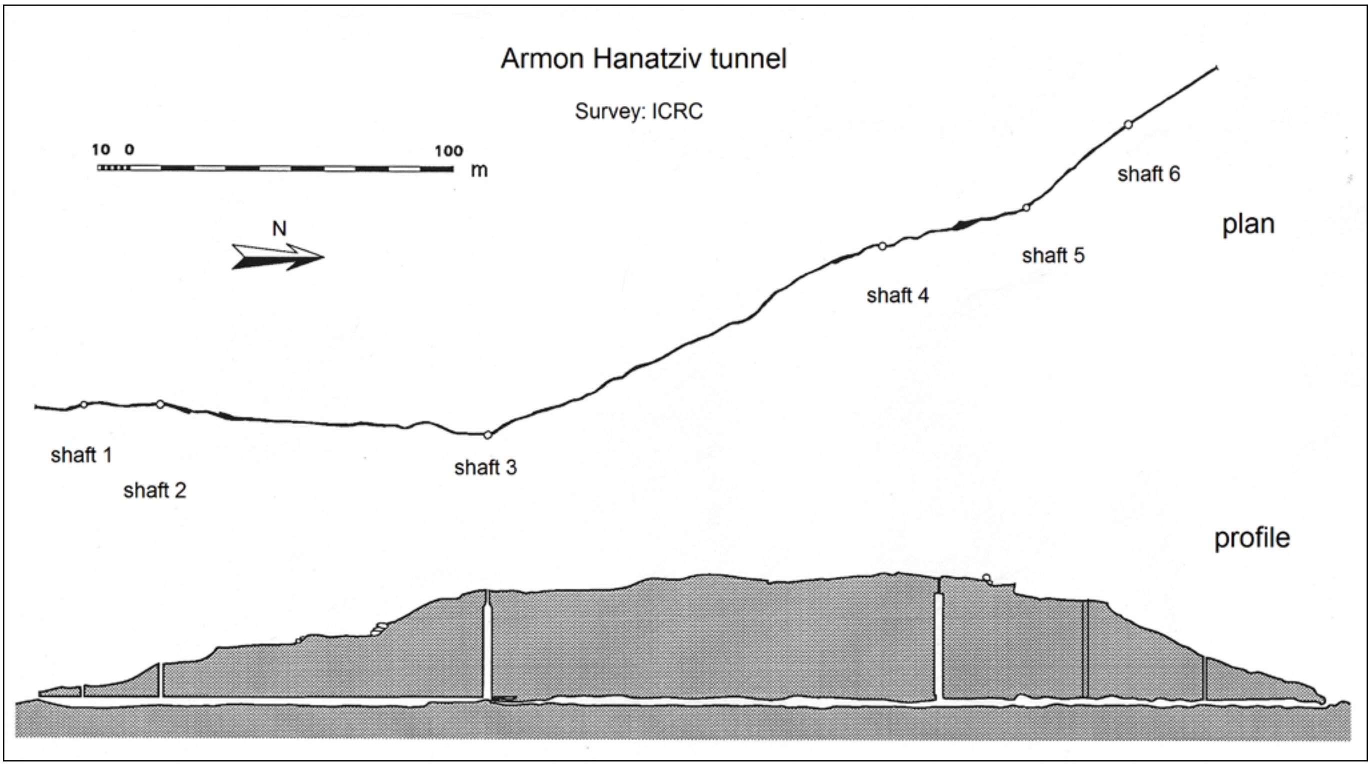

Fig. 3: Armon Hanatziv tunnel, plan and profile. Meeting points are hard to observe, and the deviations at meeting points are negligible.

Fig. 3: galleria Armon Hanatziv: pianta e profilo. I punti di incontro sono difficili da individuare, e le relative deviazioni trascurabili.

Hence the meeting points of teams are difficult to identify. ICRC survey (unpublished, Fig. 3) shows slight changes in direction between shafts, without significant horizontal deviations. This indicates accurate planning, survey and construction works on the original tunnel. Slight horizontal errors, up to few tens cm, may have been obscured by later modifications of the tunnel.

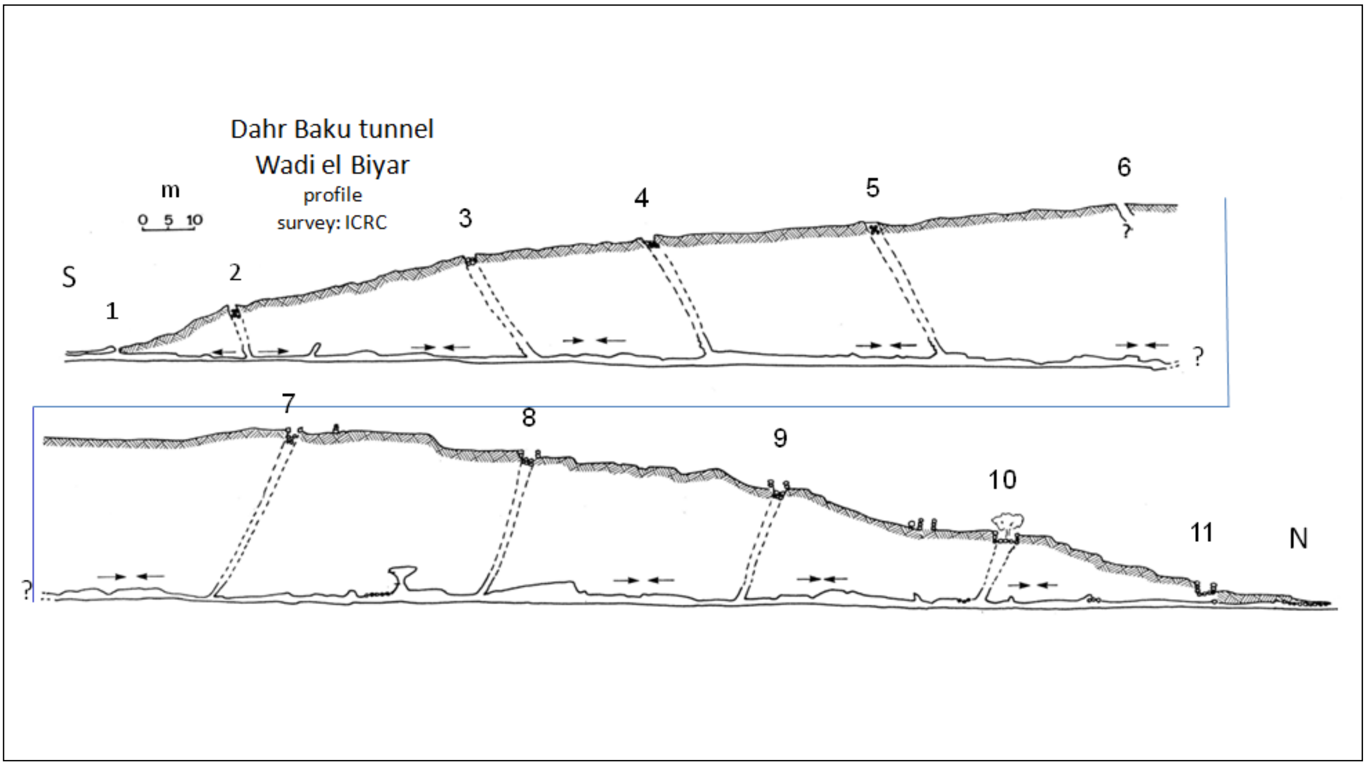

Fig. 4: Dahr Baku tunnel profile (modified after Tsuk et al., 1986). Meeting points are indicated by arrows, showing excavation direction. Note the systematically inclined shafts (numbered), except the short vertical shafts 1 and 11.

Fig. 4: Dahr Baku: profilo della galleria (modificato, da Tsuk et al., 1986). I punti di incontro sono indicati da frecce, che puntano alla direzione di scavo. Da notare i pozzi sistematicamente inclinati (numerati), ad eccezione dei brevi pozzi verticali 1 e 11.

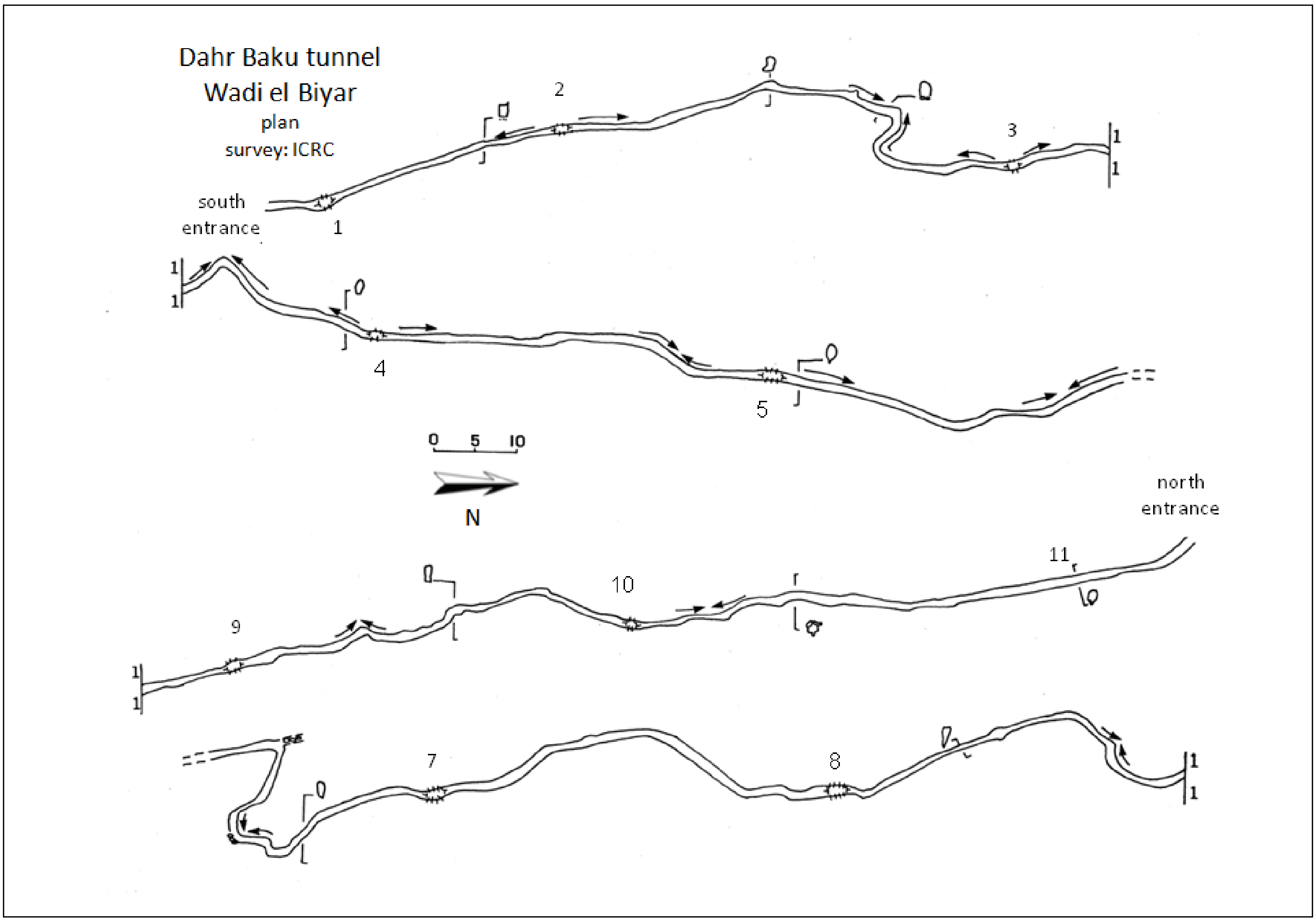

Fig. 5: Dahr Baku tunnel plan (modified after Tsuk et al., 1986). Large deviations at meeting points are evident, e.g. left of shaft 7 and between shafts 2 and 3.

Fig. 5: pianta della galleria di Dahr Baku (modificata, da Tsuk et al., 1986). Forti deviazioni ai punti di incontro sono evidenti, ad es. a sinistra del pozzo 7 e tra I pozzi 2 e 3.

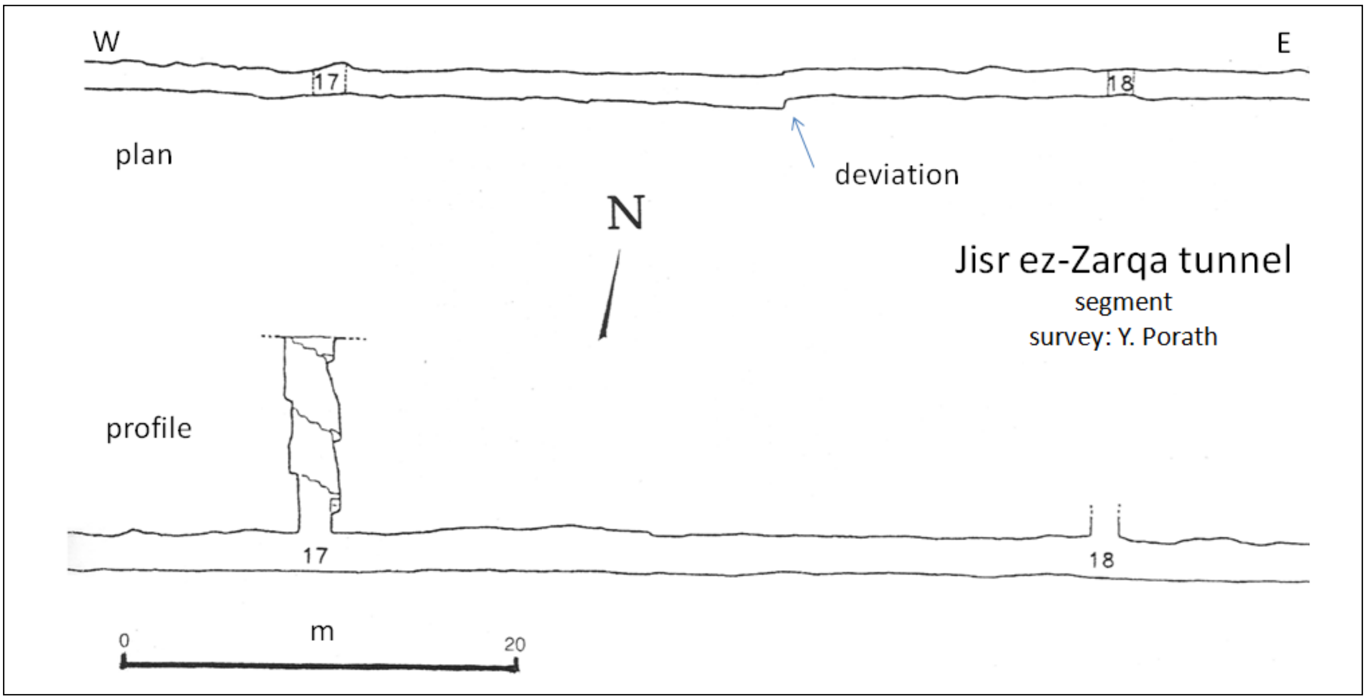

Fig. 6: a segment of Jisr ez-Zarqa tunnel in Caesarea high-level aqueduct (modified from Porath, 2002). Note the small deviation in plan view and the vertical shaft in profile. Other meeting points between shafts in this tunnel have smaller, negligible deviations.

Fig. 6: un segmento della galleria di Jisr ez-Zarqa nell'acquedotto alto di Caesarea (modificato, da Porath, 2002). Da notare la piccola deviazione in pianta e il pozzo verticale in sezione. Altri punti di incontro tra i pozzi presentano deviazioni minori.

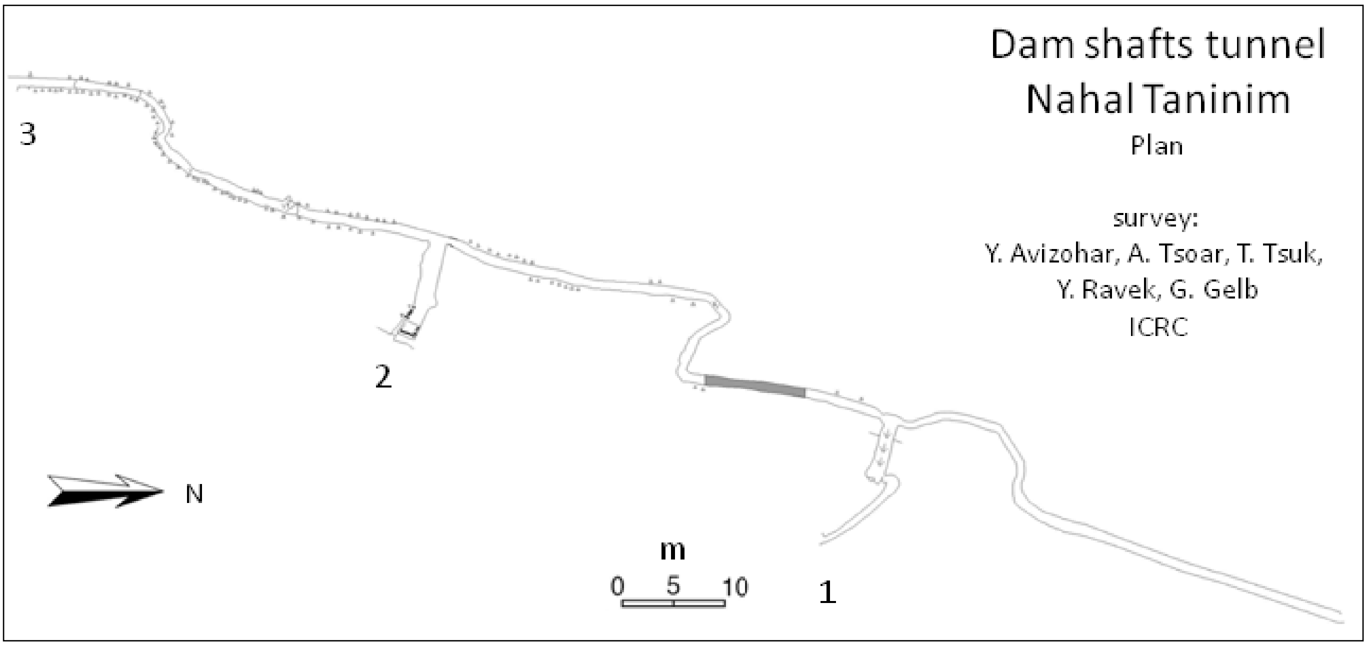

Fig. 7: plan of a segment of Taninim tunnel at the Dam Shafts (modified after Avizohar, 1993). The shafts (numbered) are inclined. Note the large (up to 8 m) deviation at meeting points.

Fig. 7: pianta di un segmento della galleria di Taninim presso la Dam Shafts (modificato, da Avizohar, 1993). I pozzi (numerati) sono inclinati. Da notare la notevole deviazione (sino a 8 m) al punto d'incontro.

Dahr Baku tunnel, Wadi el Biyar aqueduct

Wadi el Biyar aqueduct collects several water sources into the upper Solomon's Pool which supplied water to Jerusalem and Herodion (Amit, 2002). The aqueduct is attributed to the 1st century BCE (Amit, 2002; Mazar, 2002). Prior to reaching the pool, the aqueduct crosses Dahr Baku ridge via a tunnel, ~500 m long (Fig. 4).

During the ICRC study of the tunnel (Tsuk et al., 1986), its central part was blocked with mud and water, but 460 m of its length were surveyed. The tunnel had eleven shafts, most of which are observed from within the tunnel and on the surface, although they are partly blocked. The vertical height of the shafts is 1.9 to 33 m, but being inclined (except the shallow shafts 1 and 11), the actual shaft length reaches 48 m (Tsuk et al., 1986) (Fig. 4). Toolmarks show that excavation was conducted from the bottom of each shaft to both directions. The shafts are 33 to 51 m apart from each other (subaerial horizontal distance). The horizontal deviations at the junctions of the teams are up to 10.4 m (Fig. 5, Table1).

Jisr ez-Zarqa tunnel, Caesarea high-level aqueduct

Operating for ~600 years, this was the most important aqueduct leading to the Roman city Caesarea. It crossed the kurkar (sandstone) ridge of Jisr ez-Zarqa via a 442 m long quarried tunnel with 15 shafts. The tunnel was cleared and studied by Yosef Porath (2002). Toolmarks show that excavation was conducted from the bottom of each shaft to both directions. The shafts are vertical, 6.6 to 13.4 m deep, situated 11.5 to 37.4 m apart from each other. The horizontal deviations at the junctions of the teams are mostly negligible with a maximum of 0.9 m (Fig. 6). The tunnel is attributed to the 1st century CE (Porath, 2002).

The tunnels of upper Nahal Taninim

This tunnel system has been constructed to collect water from springs and the Eocene aquifer and convey it to Caesarea (Porath, 2002) and possibly for local agriculture (Siegelman, 2002). The tunnels were constructed along the sides of tributaries of Nahal Taninim, at the water table. The date is not known accurately, but most probably it belongs to the Roman period and postdated construction of the original high-level aqueduct of Caesarea, to which this system added its water (Porath, 2002). The system consists of several km long tunnels connected to the surface by inclined, stepped shafts. Most of the system is inaccessible to researchers due to mud and water filling. Tool marks show that tunnel digging was conducted from the bottom of each shaft to both directions.

Several segments of the system were surveyed by the ICRC (Frumkin, unpublished survey 1989; Avizohar, 1993; Piner, 1998) and Siegelman (2002), following partial clearing of the system. Here we analyze two segments: the Dam shafts tunnels (Fig. 7) and En Ami (Fig. 8) (Piner, 1998). The shafts are few m deep, situated 30-50 m apart. The horizontal deviation between the two teams close to the junctions is commonly up to 8 m.

Results and discussion

Our sample of 21 segments of tunnels between vertical shafts has a mean angular deviation of 0.04+/-0.19 degrees. This represents a negligible deviation in most cases, and a small, measurable deviation in one segment (between shafts 17 and 18 at Jisr ez-Zarqa).

On the other hand, our sample of 15 segments of tunnels between inclined shafts has a mean angular deviation of 7.7+/-5.9 degrees. This large deviation reflects the large meeting error in many studied segments between

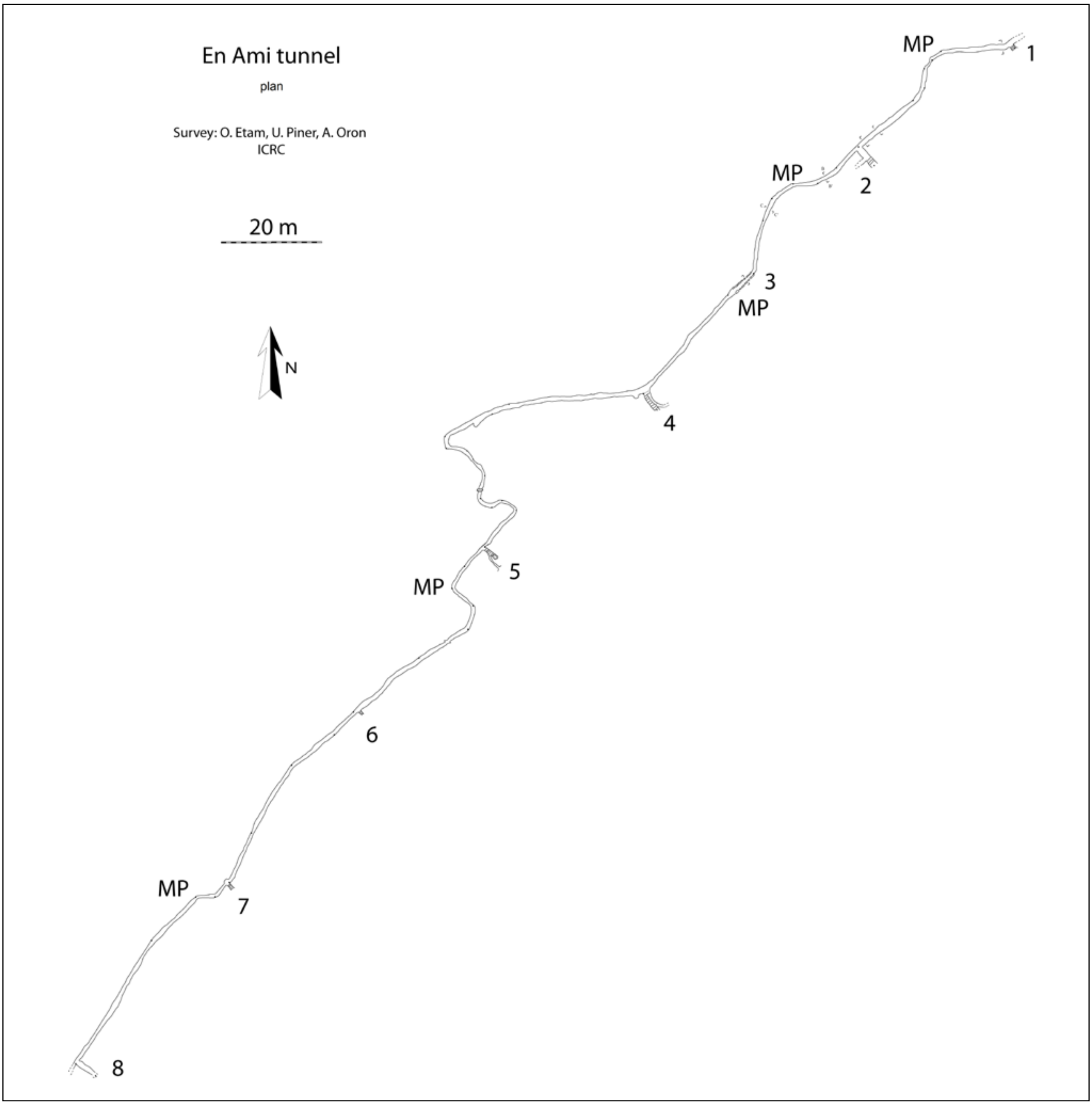

Fig. 8: plan of a segment of Taninim tunnel at En Ami. MP indicates a meeting point of two teams (modified after Piner, 1998). The shafts (numbered) are inclined. Note the large deviation at meeting points.

Fig. 8: pianta di un segmento della galleria di Taninim presso En Ami. MP indica il punto di incontro delle due squadre (modificato, da Piner, 1998). I pozzi (numerati) sono inclinati. Da notare la notevole deviazione al punto d'incontro.

inclined shafts.

Tunnel segments connecting a vertical shaft and an inclined one have no measurable deviation, as these shafts are relatively shallow close to the tunnel entrances.

The variability of angular deviation can be explained only by the vertical vs. inclined shafts constructional difference. Other variables (such as construction period, locality, importance of the water system, or its purpose) do not explain the observed angular deviation. The significant difference in tunnel deviations between vertical and inclined shafts indicate that the form of the shaft is the major contributor to the survey error during construction of the water system. This appears to reflect the importance of the way the direction of the planned tunnel is transferred from the surface through the shaft into the tunnel.

The small error associated with vertical shafts indicates a simple transfer of the direction, virtually without error. This could be accomplished using two plumb-lines hanging from a horizontal rod through the shaft. Extending through the entire shaft, with a bowl of water at the bottom to attenuate the movements of the plumb-bobs, the two vertical lines define a horizontal (or inclined) line of sight. This line of sight is virtually identical at the top (planned subaerial tunnel line) and bottom (executed tunnel) of the shaft. Consequently, no significant error was involved in transferring the designed direction of the tunnel from the surface to the bottom of the vertical shaft. The two long plumb-lines could have been a standard part of a *groma* kit, such as was unearthed at the surveyors office in Pompeii (Isaac, 1958).

Inclined shafts prevented the use of plumb-lines throughout the entire shaft. Not surprisingly, the large angular deviations of the associated tunnels, show that transferring the designed direction of the tunnel from the surface to the bottom of the inclined shaft was not accurate enough. A *dioptra* for angles measurement coupled with a distance measurement device could be used for such a multi-leg survey, together with a knowledge of trigonometry. However, this would still involve several sources of error. Moreover, if the surveyors distrusted or did not possess the elaborate *dioptra*, than the errors would increase further.

Where vertical shafts were used, the high accuracy of the tunnels based on the inferred plump-line surveying technique can also indicate the subaerial survey method. Optical sighting survey across the ridge would be the most probable method, rather than on some type of triangulation around the ridge.

In conclusion, it has been shown that vertical shafts are a better choice in terms of tunnel survey and construction. However, there must be a reason why inclined shafts were preferred (over vertical ones) in some occasions. A possible reason for this could be the need to descend the shafts for regular maintenance of the tunnel where this was needed. The inclined shafts had steps which allowed easier access into the tunnel. The deviations associated with inclined shafts could be overcome by acoustic communication between the two teams, which was an old practice (Frumkin and Shimron, 2006).

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References

Amit D., 2002, *New data for dating the High-level aqueduct, the Wadi el Biyar aqueduct, and the Herodion aqueduct.* Journal of Roman Archaeology Supplementary Series, vol. 46, 253-266.

Billig Y., 2002, *The Low-level aqueduct to Jerusalem: recent discoveries*. Journal of Roman Archaeology Supplementary Series, vol. 46, 245-252.

Avizohar Y., 1993, *Mapping the Dam Shafts.* Niqrot Zurim, vol. 19, 44-48.

Bromehead C. E. N., 1942, *The early history of water supply*. Geographical Journal, vol. 99, 183.

Davey C. J., 1985, *The Negüb tunnel*. IRAQ, vol. 47, 49-55.

Del Prete S., Parise M., 2013, *An overview of the geological and morphological constraints in the excavation of artificial cavities.* In: Filippi M., Bosak P. (Editors), Proceedings 16th International Congress of Speleology, Brno, 21-28 July 2013, vol. 2, 236-241.

Forbes R. J., 1956, *Hydraulic engineering and sanitation.* In: Singer C., 2000, *A history of technology*, vol. 2, Oxford.

Frumkin A., Shimron A., 2006, *Tunnel engineering in the Iron Age: geoarchaeology of the Siloam Tunnel*. Jerusalem. Journal of Archaeological Science, vol. 33, 227-237.

Frumkin A., Shimron A., Rosenbaum J., 2003, *Radiometric dating of the Siloam Tunnel, Jerusalem.* Nature, vol. 425, 169-171.

Kienast H., 1984, *Hezekiah's water tunnel and the Eupalinos tunnel of Samos - a comparison.* Leichtweiss-Institut für Wasserbau der Technischen Universität Braunschweig Mitteilungen, vol. 82, 1-20.

Mazar A., 2002, *A survey of the aqueducts to Jerusalem.* Journal of Roman Archaeology Supplementary Series, vol. 46, 211-244.

Oleson J.P., 2008, *Engineering and technology in the classical world*. Oxford Un. Press.

Parise M., 2011, *Managing water resources in the karst of southern Italy: an historical survey*. Proceedings H2Karst, 9th Conference on Limestone Hydrogology, Besançon (France), 1-3 september 2011, 383-386.

Parise M., Bixio R., Burri E., Caloi V., Del Prete S., Galeazzi C., Germani C., Guglia P., Meneghini M., Sammarco M., 2009, *The map of ancient underground aqueducts: a nation-wide project by the Italian Speleological Society.* Proceedings 15th International Congress of Speleology, Kerrville (Texas, USA), 19-26 July 2009, vol. 3, 2027-2032.

Parise M., Galeazzi C., Germani C., Sammarco M., 2013, *Hydraulic works: the Map of the Ancient Underground Aqueducts*. Opera Ipogea, no. 1, 21-28.

Piner U., 1998, *The tunnel of En Ami (Nahal Taninim).* ICRC Report 3/1998, The Hebrew University of Jerusalem.

Pliny G.S., 1963, *Natural History*. Loeb Classical Library, London.

Porath Y., 2002, *The water-supply to Caesarea: a reassessment.* Journal of Roman Archaeology Supplementary Series, vol. 46, 105-129.

Reade J., 1978, *Studies in Assyrian geography, Part 1: Sennacherib and the waters of Ninveh.* Revue D'Assyriologie Orientale, vol. 72, 47-72, 157-175.

Safar F., 1947, *Sennacherib's project for supplying Erbil with water*. Shumer, vol. 3, 23-25.

Siegelman A., 2002, *Appendix: The tunnels of Taninim and Snunit.* Journal of Roman Archaeology Supplementary Series, vol. 46, 130-140.

Singer C., 2000, *A history of technology*. Vol. 2, Oxford.

Tsuk T., Miron Y., Wolovelsky K., 1986, *Biar aqueduct survey*. Niqrot Zurim, vol. 13, 109-129.

Vitruvius, *The Ten Books on Architecture, book VIII*, translated by M. H. Morgan, 1960, Dover, New York.

White K.D., 1984. *Greek and Roman Technology*. Thames and Hudson.